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Solar energy in Andalusia (Spain): present state and prospects for the future

Ángel Ramos Ridao*, Ernesto Hontoria García, Begoña Moreno Escobar, Montserrat Zamorano Toro

Department of Civil Engineering, E.T.S.I.C.C.P., Campus de Fuentenueva s/n, Section of Environmental Technology, University of Granada, 18071 Granada, Spain

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Abstract

The unsustainability of the present production–consumption energy model highlights the finite nature of conventional energy resources, as well as the environmental degradation inherent in such a model. Today's environmental policies are largely devoted to fostering the development and implementation in Europe of renewable energy technologies. This paper analyses the present and future situation of renewable energy resources in Andalusia in the south of Spain, and more specifically, of solar energy with an average potential radiation of $4.6 \pm 0.3\,\mathrm{kW\,h/m^2}$ per day. In Andalusia energy policies are generally implemented through regional development plans such as the *Plan Energético de Andalucía* (PLEAN)[1] and the *Programa Andaluz de Promoción de Energías Renovables* (PROSOL).[2] The principle objective of the latter programme is to implement and increase high-temperature solar thermal energy to 100 MW in 2006, even raising it to 230 MW in 2010. Regarding low-temperature solar thermal energy installations, there are plans to increase the quantity of $m^2/1000$ installed per inhabitant from the present figure of 14 to a total of 142. Regarding individual installations of solar photovoltaic energy, the present aim is to cover 20.4% of the national objectives and 15% in installations connected to the electricity network. The geographic location of Andalusia in the south of Spain signifies that it is in a key position to play an important strategic role in the implementation of renewable energy technology in Europe, as well as providing sufficient energy for its own needs and even exporting such projects to other countries.

Keywords: Renewable energy; Solar energy; Andalucía

*Corresponding author. Tel.: +34 958 240463; fax: +34 958 246138.
E-mail address: ramosr@ugr.es (Á.R. Ridao).

[1]Energy Development Plan for Andalusia.
[2]Andalusian Programme for the Development of Renewable Energies.

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Contents

1. Introduction

All activities require energy. Throughout the centuries the availability, utilization, and discovery of new energy sources have accompanied and even been the force behind important technological, economic, and social changes in the history of mankind. Significant examples are animal power in ancient times, eolian energy for ships and windmills during the Renaissance, hydraulic energy and coal in the 19th century, and finally, oil, natural gas, and nuclear energy in the 20th century.

The unsustainability of the present production–consumption energy model highlights the finite nature of conventional energy resources, as well as the environmental degradation inherent in such a model [1].

Energy consumption in developed countries grows at a rate of approximately 1% per year, and that of developing countries, 5% per year [2]. Present reserves of oil and natural gas can only cover consumption at this rate for the next 40 years in the case of oil, and for the next 60 in the case of natural gas.

From a purely environmental perspective, the emissions currently generated by the use of fossil fuels are the source of serious environmental problems (e.g. acid rain, the greenhouse effect, holes in the ozone layer), which in many cases are irreversible [2–4].

The Kyoto Protocol is part of the United Nations Framework Convention on Climate Change. Its principal objective is to get developed nations to reduce their greenhouse gas emissions [4,5]. In Europe energy-associated environmental problems have been dealt with in a variety of action plans, but especially in the Sixth Environment Action Programme of the European Community (2001), *Environment 2010*: *Our Future*, *our Choice* [5].

Increased use and promotion of renewable energy technologies (solar thermal, biomass, wind, hydroelectricity) seem to be a viable solution for environmental problems produced by other energy sources. For this reason, current policies focus on fomenting their development and use in Europe as stated in the following: (1) Directive 96/92/EC establishing common rules for the internal market in electricity; (2) Directive 98/30/EC establishing common rules for the market for natural gas; (3) Directive 2001/77/EC on the promotion of electricity produced from renewable energy sources in the internal electricity market; (4) White Paper: *An Energy Policy for the European Union*.

In Spain the advancement of renewable energy technologies is based on various sets of regulations, among which are the *Plan de Fomento de Energías Renovables* (PLAFER)[3] and the *Real Decreto* 2818/98 regarding the production of electricity for installations supplied by sources of renewable energies, waste products, and cogeneration.

The Autonomous Community of Andalusia, one of whose competencies is to create and implement policies regarding energy use, has been developing work plans over the past years regarding the planning, organization, and coordination of actions in this area.

2. The energy situation in Andalusia

2.1. Geographic location

Mainland Spain has a surface area of 493.486 km^2. Administratively speaking, it is divided into 17 autonomous communities and 52 provinces. The Autonomous Community of Andalusia is located in the south of Spain between latitudes 37 y 42°N (see Fig. 1), covering a total area of 87.268 km^2, approximately 17.68% of the whole country. It is made up of the provinces of Almeria, Cadiz, Cordoba, Granada, Huelva, Jaen, Malaga, and Seville. Not surprisingly, it is also the most densely populated autonomous community in Spain as it represents 18% of the national population.

2.2. Energy infrastructure

If devices that transform primary energy into final energy can be regarded as energy exploitation installations, the total electrical power capacity available in existing installations in the Autonomous Community of Andalusia amounts to 5201.3 MW. Table 1 shows the total electric power capacity, as well as a list of the sources that generate it.

Regarding solar energy, Andalusia has the highest number of solar thermal panels installed of any other region in Spain, with a total surface of 130552 m^2 of low-temperature solar thermal energy, and electrical power in the form of solar photovoltaic energy of 3618 kWp, which generates 6512 MWh [6]. In the former, the domestic sector is 64% of the total. In the later case, 93.2% are individual installations, and the other 6.8% are connected to the electricity network. Fig. 2 shows the distribution of solar energy in the provinces belonging to the Autonomous Community of Andalusia.

The development of solar energy in the Autonomous Community of Andalusia is supported by the *Plataforma Solar de Almería* (PSA),[4] a division of the *Centro de Investigaciones Energética, Medioambientales y Tecnológicas* (CIEMAT).[5] This is the largest research and development centre in Europe, devoted to high-concentration solar energy technologies. The PSA has been functioning since the 1980s, and is regarded as an important line of research within the structure of the Department of Renewable Energies of the CIEMAT.

Table 2 shows the description of the transport system and the distribution of electrical energy in the Autonomous Community of Andalusia.

[3] Plan for the Promotion of Renewable Energies.
[4] Solar Platform of Almeria.
[5] Energy, Environmental, and Technological Research Centre.

Fig. 1. Geographical location of the Region of Andalusia.

Table 1
Electrical power capacity available in the Autonomous Community of Andalusia as of 1/01/2000 [6]

	MW
Hydraulic (ordinary regime without pumping)	474.7
Pumping	570.0
National coal-fired power stations	324.8
International coal-fired power stations	1712.0
Biofuel power plants	1133.0
Subtotal: ordinary regime	4217.5
Cogeneration (without biomass)	695.8
Hydraulic (special regime)	77.8
Wind	146.2
Solar photovoltaic	3.6
Biomass	51.3
Thermal (other waste products)	12.1
Subtotal: special regime	986.8
Total electrical power capacity	5201.3

Quality of service in the electrical system is measured by Interruption Time Equivalent to the Power Installed (TIEPI) [7]. Most of the provinces in Andalusia have TIEPI values above the national average, due to the large areas of rural population, which suffer from occasional supply problems. Nevertheless, in recent years there has been a marked improvement in the TIEPI in this respect (PLEAN).

2.3. Energy consumption and demand

The final energy consumption in Andalusia in 2000 amounted to 11569.3 ktep. As shown in Fig. 3, oil-bearing products are in the first position, followed by electricity and natural gas. During this same time period, renewable energies accounted for 648.9 ktep, according to the data shown in Fig. 4. On the basis of this information, the rate of energy self-sufficiency in the Autonomous Community of Andalusia was 9.8%.

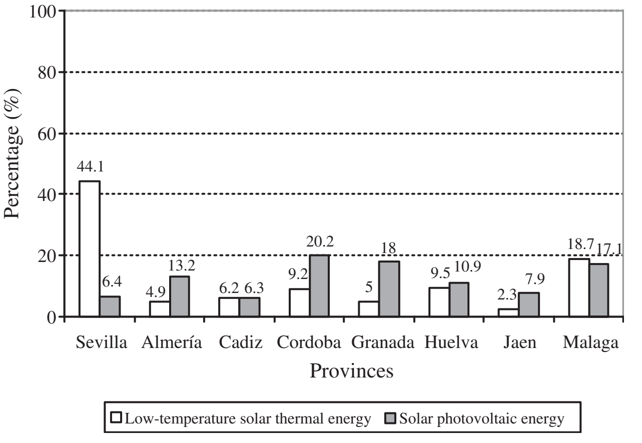

Fig. 2. Low-temperature solar thermal energy and solar photovoltaic energy (31/12/2000) [6].

Table 2
Description of the transport system and the distribution of electrical energy in the Autonomous Community of Andalusia as of 1/01/2000 [6]

High tension power lines	
Tension (kV)	Length (km)
400	1154
220	2564
132	2583
66–50	5486
Substations	
Tension (kV)	Power (kVA)
400/220	5520000
400/132	180000
220/132	2200000
220/66–50	3160000
220/20	80000
132/66–50	2660000
132/M.T	1301000
66/50	605000
66–50/M.T	6928500
Other tensions	161500
Installations $<36\,\mathrm{kV}$	
	Power (kVA)
Medium-tension aerial power lines (kms)	33255
Medium-tension underground power lines (kms)	7440
Low-tension aerial power lines (kms)	48740
Low-tension underground power lines (kms)	12277
Electrical transformation centres (number)	52113
Power generated by electrical transformation centres (kVA)	13462089

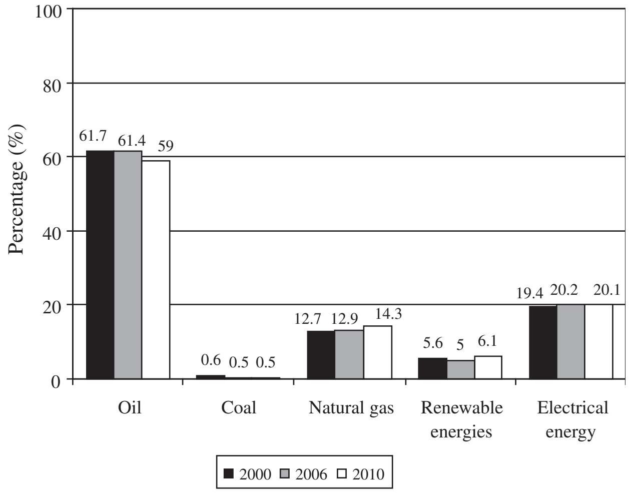

Fig. 3. Final energy demand in 2000 and predicted for 2006 and 2010 in Andalusia [6].

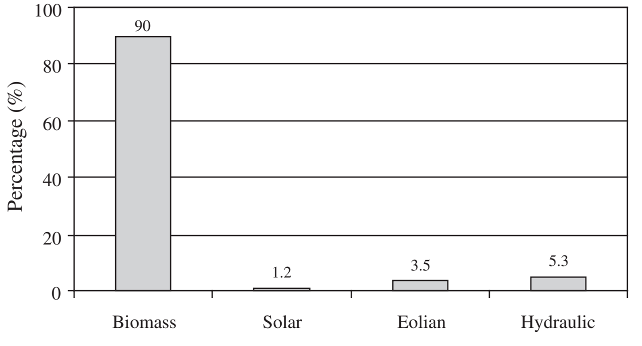

Fig. 4. Contribution of renewable energies to the structure of energy consumption in Andalusia [6].

The foreseeable increase in the consumption of primary energy in Andalusia in 2001–2006 is estimated at 23.5%. However, if the time period is extended to 2010, the total increase can be calculated at 33.9%. Fig. 3 shows the final energy demand for 2006 and 2010. According to these calculations, the increase in consumption of natural gas and renewable energies is relatively high. These predictions highlight the fact that in the coming years Andalusia will no longer need to import electrical energy, and will even begin to export it.

2.4. Renewable energy policy in Andalusia

In 1995 the *Plan Energético de Andalucía*[6] (1995–1999) was approved, which lasted until 2000. Subsequently, a second energy plan *Plan Energético de Andalucía* 2003–2006 (PLEAN) went into effect, as specified in the *Real Decreto* 86/2003. This plan has the

[6]Energy Development Plan for Andalusia.

advantage of incorporating the objectives agreed upon by the European Union in its White Paper, the Directive 2001/77, and the Plan for the Advancement of Renewable Energies proposed by the Spanish government. It also contributes to the fulfilment of the commitments of the European Union to the Kyoto Protocol.

The PLEAN 2003–2006 seeks to bring together all of the directives that articulate the actions regarding energy that will be carried out in Andalusia during the stated time period. Among the general criteria underlying this plan are respect towards the environment and diversification of energy sources. In this sense Andalusia is committed to making use of the abundant renewable energy resources available in the region, establishing a participation of 15%. The high rate of participation of renewable energies is expected to take place homogeneously.

This plan has been designed with a view to modifying the energy system in Andalusia though the following operational objectives: (1) to guarantee the electrical power supply for all of the inhabitants of the region of Andalusia; (2) to foment conservation and efficiency in energy use; (3) to respect the environment; (4) to progress towards energy diversification; (5) to improve regional infrastructures related to energy generation, transportation, and distribution; (6) to promote a competitive industrial network; (7) to raise awareness in the population regarding renewable energies.

All of these points are reflected in the following general objective formulated in the Energy Plan: to achieve an energy system in Andalusia, which is sufficient, rational, efficient, renewable, diversified, and respectful of the environment.

3. Solar energy in Andalusia

3.1. Natural potential for solar energy

Solar radiation is evidently a determining factor when it comes to studying the natural potential for solar energy in a certain region. With a view to discovering this potential for Andalusia, we analysed data from 68 climate stations distributed throughout the region, as shown in Fig. 5, and with the characteristics listed in Table 3. The period of study includes information regarding solar radiation (MJ/m^2 per day) from 1999 until the present.

The analysis of data shows that the average solar radiation potential for this region is $16.4 \pm 1.2\,MJ/m^2$ per day. The isoradiation map in Fig. 5 highlights the fact that solar radiation is distributed very evenly throughout the entire region. In fact, it is equal to an average solar energy potential of $4.6 \pm 0.3\,kW\,h/m^2$ per day. However, statistically significant differences were observed for each season of the year, maximum average values during the summer of $23.2 \pm 2.0\,MJ/m^2$/day and minimum average values during the autumn of $10.4 \pm 0.9\,MJ/m^2$ per day. Fig. 6 shows the solar radiation distribution for each season of the year throughout Andalusia. The maximum average energy potential obtained in the summer is $6.5 \pm 0.5\,kW\,h/m^2$ per day. At similar latitudes, studies made in Turkey [8] and Jordan [9] found average solar radiation values of 3.6 y 5–7 $kW\,h/m^2$ per day, respectively, which were similar to those obtained for southern Spain.

The amount of solar radiation in the region means that it would be feasible to consider solar energy as a potential energy source for different domestic uses [1,2,10–12], factories and commercial buildings [12] in the form of individual photovoltaic solar panels or systems [11].

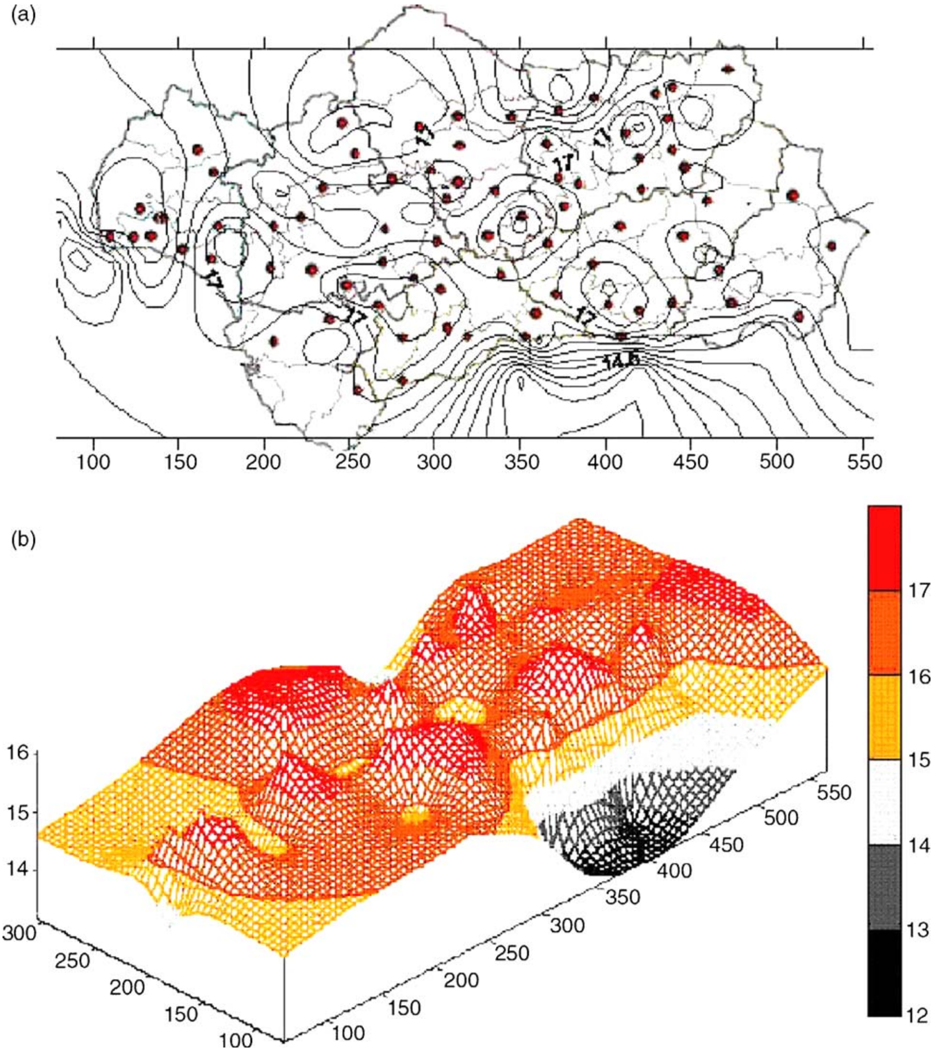

Fig. 5. Map of the annual average of isoradiation in MJ/m^2 per day in Andalusia (a) 2D and (b) 3D.

3.2. Population distribution

The urban system in Andalusia has two negative aspects, which are an obstacle to coherent regional organization: (1) the gradual breakdown of population settlements and the lack of functional impetus of towns in mountain and rural farming areas; (2) the yawning gap between the dynamic nature of the system of population settlements and the establishment of an organizational policy to regulate them.

The network of cities in Andalusia can be said to be divided into two opposing levels: (1) a higher relatively dynamic level consisting of the capital cities of each province; (2) a secondary regional network of small population centres of lesser importance, where

Table 3
Geographic and climatic parameters for stations located in southern Spain

Station	Latitude °North	Longitude West	Altitude (m)	Station	Latitude °North	Longitude °West	Altitude (m)
San Isidro	36°41′	2°16′	120	Villaviciosa Córdoba	38°3′	5°	695
Antas	37°15′	1°54′	125	Obejo	38°6′	4°46′	727
Alahama de	36°57′	2°32′	360	Montoro	38°	4°2′	200
Almería Abla	37°8′	2°46′	840	Estepona	36°27′	5°6′	45
Chirivel	37°35	2°15′	1080	Cártama	36°43′	4°38′	90
Motril	37°1′	4°3′	35	Rincón de la Victoria	36°42′	4°14′	30
Alhama de Granada	36°43′	3°29′	935	Periana	36°55′	4°1′	550
Orgiva	37°24′	3°16′	400	Ronda	36° 51′	5°14′	540
Lecrín	37	3°31′	467	Campillos	37°	4°51′	460
Santa Fe	37°11′	3°42′	580	Villanueva de Algaida	37°1′	4°28′	480
Montefrío	37°2′	4°4′	841	Limena de La Frontera	36°24′	5°26′	75
Iznalloz	37°27′	3°33′	980	Jerez de la Frontera	36°43′	6°9′	35
Guadix	37°17′	3°5′	1000	Villamartín	36°5′	6°37′	150
Zújar	37°41′	2°52′	850	Olvera	36° 56′	3°15′	623
Castillo de Locubín	37°31′	4°57′	700				
Montellano	36° 59′	5°28′	210				
Martos	37°42′	4°24′	380	Puebla de Cazalla	37°7′	5°17′	250
Huelma	37°4′	3°24′	800	Estepa	41°34′	3°3′	300
Quesada	37°52′	3°3′	700	La Lantejuela	37°19′	5°17′	135
Higuera de Arjona	37°58′	3°59′	360	Utrera	37° 5′	5°53′	10
Bedma-Garcíes	37°47′	3°24′	650	Puebla del Río	40°	3°	20
Peal del Becerro	37°53′	3°9′	460	Espartinas	37°23′	6°9′	150
Baeza	37°55′	3°32′	400	Tocina	37°36′	5°43′	25
Villacarrillo	38°3′	3°	670	Puebla de los Infantes	37°48′	5°24′	350
Andujar	38°2′	4°5′	190	Alanis	38°1′	5°41′	728
Guarromán	38°11′	3°4′	350	Aracena	37°52′	6°3′	550
Santiesteban del Puer Sant. del Puerto	38°1′	3°11′	575	Río Tinto	37°41′	6°36′	350
Cast. de Santisesteban	38°16′	3°32′	699	San Bartolomé Torre	37°23′	7°8′	122
Torres de Albanchez	38°23′	2°39′	700	Gibraleón	37°23′	6°52′	52
Lucena	37°19′	4°27′	435	Bollullos	37°19′	6°32′	80
Carcabuey	37°25′	4°15′	630	Almonte	37°6′	6°3′	20
Nueva Carteya	37°35′	4°24′	405	Moguer	37°9′	6°51′	23

Table 3 (*continued*)

Station	Latitude °North	Longitude West	Altitude (m)	Station	Latitude °North	Longitude °West	Altitude (m)
Santaella	37°27′	4°53′	190	Cartaya	37°2′	7°9′	73
La Rambla	42°4	3°39′	280	Ayamonte	37°14′	7°2′	30
Guadalcazár	37°42	5°	150	Córdoba	37°48′	4°26′	281

relatively little change takes place. Two exceptions to this general rule are the urban clusters of population around the larger cities and the areas along the coast.

In the Autonomous Community of Andalusia 83% of the cities have a population of less than 10,000 inhabitants, representing 23% of the total population in the region (see Fig. 7). Regarding its location, 22% of this distribution can be found in farming areas in the interior, and 9.6% in remote mountainous areas of difficult access, which presents a problem for conventional energy supply (see Table 4). This is one more indication of the size of the potential market and the importance of renewable energies as a self-sufficient energy source. As previously mentioned, solar energy is one of the most viable of these sources, given its homogeneous distribution throughout the region of Andalusia.

3.3. *Promotion of solar energy by the regional government*

Andalusia is in urgent need of an adequate energy infrastructure so that the region can achieve higher levels of economic development. This would allow all of its inhabitants access to a quality energy supply, irrespective of their place of residence.

Crucial objectives are targeted at eliminating the current dependency on oil (61.7%), substantially increasing and enhancing the contribution of renewable energies (5.6%), and favouring energy self-sufficiency.

The Andalusian Regional Government has been promoting the use of renewable energy by means of a series of laws and official programmes. The one currently in force is a decree issued on April 5, 2001, which establishes the rules and regulations for financial grants from the *Programa Andaluz de Promoción de Instalaciones de Energías Renovables* (PROSOL)[7] during 2000–2006. PROSOL has two sources of funding: on the one hand, it is included within the actions supported and financed by the European Regional Development Fund (FEDER), whereas on the other, it also receives funds from the Andalusian Regional Government.

Objectives achieved by PROSOL [14] up until 2002 have been the installation of 21,382 m^2 of solar thermal collectors for water heating, 360 kWp of individual solar photovoltaic installations as well as 113 kWp of solar photovoltaic installations connected to the electricity network.

Subsequently, as PROSOL [14] developed, a decree was published on January 24, 2003 that established the rules and regulations for obtaining funding for the promotion of renewable energy installations with a focus on solar energy, for example, solar thermal

[7] Andalusian Programme for the Development of Renewable Energies.

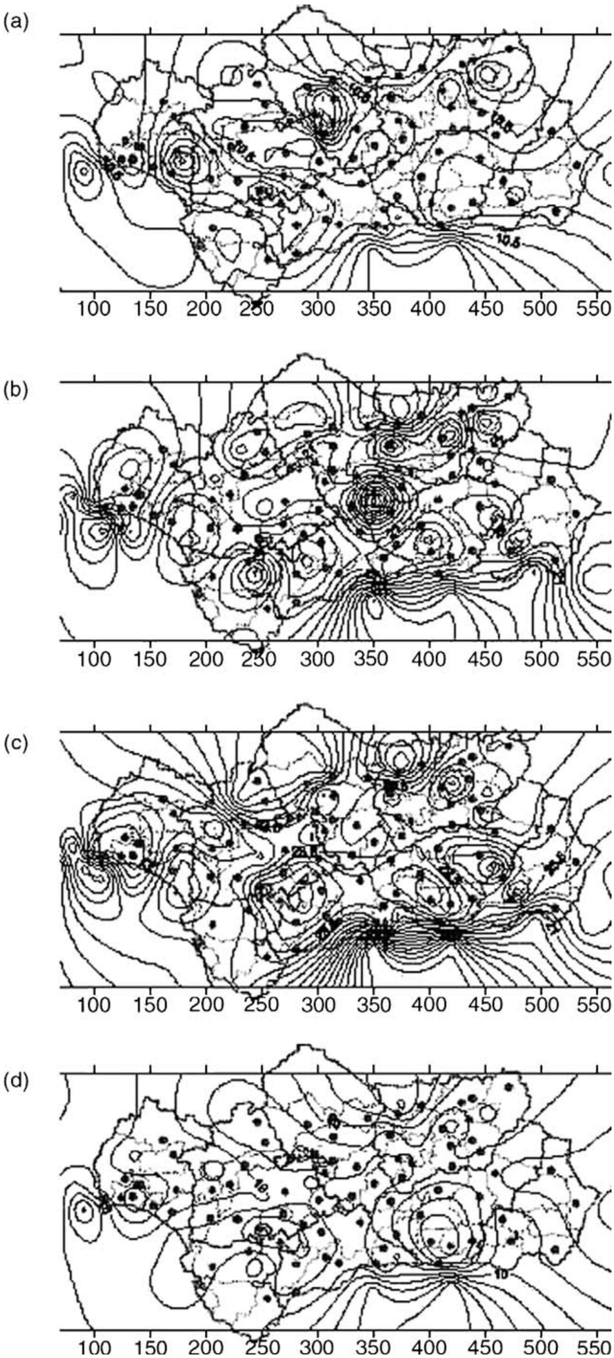

Fig. 6. Map of the annual average of isoradiation in MJ/m^2 per day for the seasons of the year: (a) winter (b) spring (c) summer and (d) autumn.

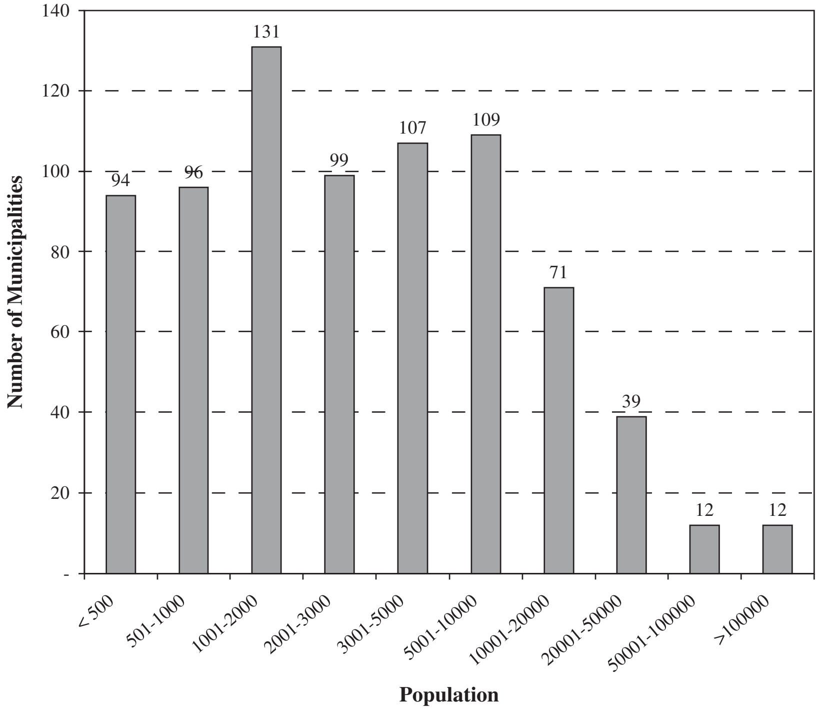

Fig. 7. Distribution of the population and of municipalities in Andalusia according to the number of residents in each province [13].

Table 4
Population distribution according to size of municipality (2001) [12]

	(%)
Rural farming areas	22,0
Coastal areas	12,3
Mountain areas	9,6
Urban areas	56,1

installations for heating water, individual solar photovoltaic installations which are located at more than 500 m from the electricity network with a maximum power of 15 kWp in each installation.

On the basis of investment costs, this directive establishes the basis for non-recoverable financial aid with the following restrictions: (a) solar thermal installations for heating water: 500 €/m^2; (b) individual solar photovoltaic installations not connected to the public electricity network: 12 €/Wp; (c) solar photovoltaic installations connected to the public electricity network: 9 €/Wp.

In the case of solar photovoltaic installations connected to the public electricity network, the *Real Decreto* 1802//2003 [15] specifies the formats for contracts and invoices, as well as rates for electricity consumption for 2004.

The objectives established in PROSOL are focused on raising high-temperature solar energy to 100 MW in 2006 and 230 MW at the beginning of 2010. The electrical power will be obtained from solar power plants, which are exclusively solar, or from hybrid solar plants, which also use other forms of renewable or conventional energy (preferably natural gas).

Regarding low-temperature solar thermal installations, the programme plans to reach a total of 936 m^2 in 2010. In order to attain that objective it will be necessary to go from 2.5 to 25% of the potential market, participating with 22% in national objectives and increasing the figure of m^2/1000/inhab. from the current number of 14 to 142.

Regarding individual solar photovoltaic installations, the programme plans to reach a total of 4.3 MWp by 2010, which means covering 20.4% of the national objectives. In the case of solar photovoltaic installations connected to the electricity network, the objective is to reach 16.4 MWp, which could cover 15% of the national objectives for 2010.

Currently, there are various solar energy initiatives. For example, in the province of Granada, in 2004 the German company Solar Millennium AG began to construct the first two solar energy plants with parabolic concentrators in Europe, both with a capacity of 50 MW. Annually, each of these installations will be able to produce 157 GWh of pure solar energy, which will supply the public electricity network in Spain.

4. Conclusions

The high level of insolation in the region of Andalusia, the presence of the Solar Platform of Almeria, an important source of experience in solar energy techniques, as well as various projects financed and promoted by private industry are all factors that will undoubtedly give Andalusia an important role in the implementation of renewable energy technology in Europe, the capacity for providing sufficient energy for the needs of the population, and the possibility of even exporting such projects to other countries.

The population distribution in Andalusia shows that there is a great potential market for renewable energies, among which solar energy should be highlighted because of its homogeneous presence throughout the entire region.

Acknowledgements

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